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Observations of Emission Lines in

M Supergiants

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Summary

Copernicus observations of Mg II h and k emission lines from M giants and supergiants are described. Supergiants with extensive circumstellar gas shells show an asymmetric k line. The asymmetry is ascribed to superimposed lines of Fe I and Mn I. The Mg II line width fit the Wilson-Bappu relation derived from observations of G and K stars.

Results of correlated ground-based observations include (i) the discovery of K I fluorescent emission from the Betelgeuse shell; (ii) new estimates of the mass-loss rates; and (iii) the proposal that silicate dust grains must account for the major fraction of the Si atoms in the Betelgeuse shell.

1. Introduction

NSG 5005 supported a Guest Investigator program with the OAO-3 "Copernicus" satellite to observe emission lines from chromospheres around M supergiants. The ultraviolet spectroscopy from Copernicus was correlated with ground-based spectroscopy conducted at the McDonald Observatory.

2. Mg II h and k Emission

Our initial observing program was a search for several lines including C II 1037 Å, C III 977 Å, N II 1085 Å, O I 1302 Å, Fe I 2380 Å, Fe I 2395, Fe II 1145 and CO lines near 1085 Å. The bright M supergiant α Orionis was selected for this search. None of these lines were detected. Flux units are provided by Bernat and Lambert (Ap. J., 204, 830, 1976 - see Table 2).

Thanks to earlier spectrophotometry with OAO-2, we knew that the Mg II h and k resonance lines were present in M supergiants. Our initial study covered α Orionis (Betelgeuse) and α Scorpii (Antares).

The striking new result was a pronounced asymmetry of the shorter wavelength k line. We explored the possibility that the k-line asymmetry was caused by overlying resonance lines of Mn I and Fe I formed in the cool circumstellar shells around these stars. New high resolution spectra obtained at the McDonald Observatory for the Mn I resonance triplet at 4030-4033 Å showed that there are insufficient Mn atoms in the shells to produce the asymmetry in the k line. On the very reasonable assumption that the Mn/Fe abundance ratio in the shells is approximately solar, a similar conclusion was reached for the Fe I line within the k emission line.

However, our McDonald spectra confirmed Spitzer's earlier observation (Ap. J., 90, 494, 1939) of a filling-in by emission of a Fe I line at 4308 Å. The upper state of the 4308 Å line is shared with the resonance line at the k line position. It is difficult to avoid the conclusion that the emission in the 4308 Å line is fluorescence driven by the absorption of k line photons. Our quantitative analysis showed that the absorbing iron atoms are not in the circumstellar shell.

Where are they? We speculated that the iron atoms belong to a cool turbulent region sandwiched between the base of the circumstellar shell and the top of the chromosphere.

As a result of our initial study, we proposed a high resolution observation of the k line in α Orionis. At high resolution, the Fe I/Mn I lines within the shorter wavelength emission component of the double peaked k line should be resolvable as a sharp deep incision in the emission profile. In spite of several hours of observing time, the observed profile was rather noisy and detection of the sharp absorption feature was uncertain. Rather than clutter the literature with a marginal result, I decided to terminate this study. The International Ultraviolet Explorer (IUE) satellite has a high resolution ultraviolet spectrograph. Mg II profiles published by other authors indicate that the IUE spectra lack the resolution to reveal the sharp absorption feature. Fortunately, it will be resolved easily by the high resolution spectrograph on the Space Telescope.

Our Copernicus program of Mg II low resolution observations was extended to the M2 giant β Peg and the M5 supergiant α Her. The asymmetric Mg II h and k profiles in β Peg were attributed to formation in an expanding chromosphere. The k to h ratio of 1.4 suggests an optically-thick chromosphere with temperature increasing with height above the photosphere.

The α Her Mg II profiles were similar to our earlier observations of α Ori and α Sco: the k line appears asymmetric but the h line is symmetric. This lack of a common profile for h and k lines is not obviously reconcilable with an expanding chromosphere. The k line asymmetry was again contributed to absorption lines of Mn I and Fe I by atoms between the cool expanding circumstellar shells and the chromosphere.

The Fe I absorption line coincident with the weakened half of the k line is a weak intercombination transition. Absorption in this Fe I resonance line will be followed by emission in a more probable downward transition. Spectra of α Ori, α Sco and α Her show that such fluorescence fills in a line at 4307 Å. In β Peg, the 4307 Å line is not significantly weakened relative to other members of the multiplet. Therefore the 4307 Å observations show a rough correlation between the k line asymmetry and the filling in of the photospheric absorption line by fluorescent emission.

With the Mg II profiles for the four M stars, we checked that the Mg II line widths obeyed a line width - absolute visual-magnitude relation, the Wilson-Bappu effect. A published calibration (Kondo et al., Ap. J., 207, 167, 1976) gave

$$M_V = 29.97 - 12.58 \log W$$

where W (in km/s) is the full width at the base of the line. α Ori was the sole M star used in establishing the calibration. The three new M stars - α Sco, α Her and β Peg - were compared with this calibration. Absolute magnitudes were taken from Sanner (Ap. J. Suppl. 32, 115, 1976) and Bernat (Ap. J. 213, 759, 1977).

The agreement between our results and the Kondo et al. calibration was poor. Their calibration was systematically low for the brightest stars (α Ori and α Aur) included in the fit. However, an earlier calibration by McClintock et al. (Ap. J. 202, 733, 1975) fitted the new data well. We concluded that there was no evidence for systematic deviations by the luminous stars from the Mg II Wilson-Bappu effect as determined from hotter, less luminous stars.

3. Circumstellar Gas Shells

a) K I Emission

In conjunction with the Copernicus observations, we began a program of spectroscopic observations of circumstellar gas shells.

The spectroscopic signature of the gas in the expanding shell is a narrow blue-shifted absorption line in the deep core of photospheric resonance and low excitation lines. These shell lines were discovered by Adams and McCormack (Ap. J. 81, 119, 1939) and the first quantitative discussion provided by Spitzer (Ap. J. 90, 494, 1939).

Our motivation for a new study of the circumstellar absorption lines sprang largely from the capabilities of the McDonald Observatory's high resolution photoelectric spectrometer. We discovered a novel way in which to probe the shell.

When an atom in the shell absorbs a resonance line photon, the photon must be reemitted almost simultaneously. Collisional deexcitation at the very low particle densities prevailing in the shell is not competitive with photon reemission. If the shell subtends a large enough angle on the sky, resonance line fluorescent emission should be observable. Now, Deutsch (Ap. J. 132, 210, 1956) in a classic paper dealing with the binary system, α Her A and B, showed that the shell around the M supergiant (α Her A) envelops the G-type companion. A direct inference was that the shell has an outer radius of at least $200 R_S$ where R_S is the radius of the M supergiant. The inner radius of an expanding shell is not easily estimated. Weymann (Ap. J. 136, 844, 1962) constructed an argument based on the strength of the circumstellar components to the Ca II infrared triplet lines. Our modification of his argument and application using our high resolution low noise spectra led to an estimate for the inner radius of the α Orionis shell: $R(\text{inner}) \geq 30 R_S$. The observed stellar angular diameter is $\phi_S = 0''.05$. Simple arithmetic suggested that the shell should be spatially resolved on the sky: $\phi_i = \phi_S R_i/R_S \geq 1''.5$ for $R_S > 30 R_i$.

Detection of K I fluorescent emission from the α Orionis shell was first detected on March 31, 1975. In November 1975, we mapped the K I emission out to $5''$ from the star. More recently, emission has been traced to at least $50''$ from the star. (References are given in § C).

A thorough exploitation of our discovery will be possible when a fast spectrometer is coupled to an area detector and used with a telescope at a site of excellent seeing (or, better, from space).

b) Circumstellar Absorption Lines

A. P. Bernat (UT graduate student) under the P.I.'s supervision reanalyzed the shell absorption lines to obtain the physical structure of the shells of four M supergiants α Orionis, α Scorpii, α Herculis and μ Cephei. Spectra included photographic plates from the Hale Observatories plate files, new McDonald photographic spectra and photoelectric scans. In his analysis, he recognized the spherical geometry of the shells and made detailed calculations of the radiative transfer.

Bernat's analysis showed the column densities derived from the shell absorption lines were lower than previous estimates based upon a plane-parallel approximation. The physical size of the shell was inferred through ionization modeling, Weymann's Ca II technique, and direct observation (K I emission). The size estimates exceeded previous values. The mass-loss rate, which is proportional to the product of the column density and the shell size (specifically, the inner radius), was found to be much larger than previous estimates. Bernat's results range from 6.7×10^{-7} to $4.2 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ for the 4 stars. These results have generated much interest. Bernat has continued to work in this area using observational tools from high resolution infrared spectroscopy to the International Ultraviolet Explorer.

c) Publications

Bernat, A. P. The Circumstellar Shells and Mass Loss Rates of Four M Supergiants, Ap. J. 213, 756, 1977.

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